Fermi National Accelerator Laboratory

FERMILAB-Pub-94/304-E
CDF

Limits on Z-Photon Couplings from p — $\overline{\mathrm{p}}$ Interactions at $\sqrt{s} = 1.8$ TeV

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September 1994

Submitted to Physical Review Letters

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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CDF/PUB/ELECTROWEAK/CDFR/2659
$Z\gamma$ PRL Draft
Version 8.20
September 6, 1994

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Limits on Z-Photon Couplings from $p-\overline{p}$ Interactions at $\sqrt{s}\ =\ 1.8$ TeV

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Submitted to Phys. Rev. Lett. September 7, 1994

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Abstract

We report limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings derived from an analysis of Z + photon production based upon approximately 20 pb^{-1} of $p\bar{p}$ collision data recorded by the Collider Detector at Fermilab (CDF) during the 1992/93 Tevatron Collider run. We observe good agreement with the Standard Model expectation that all $Z\gamma$ couplings are zero. Assuming that only one of the couplings deviates from zero, and that the interaction associated with such a coupling is characterized by a form factor scale, $\Lambda_Z = 500$ GeV, we derive 95% confidence level limits for the CP-conserving $ZZ\gamma$ couplings of $-3.0 < h_{30}^Z < 2.9$ and $-0.7 < h_{40}^Z < 0.7$. Similar limits are obtained for the CP-violating $ZZ\gamma$ couplings and the couplings associated with a $Z\gamma\gamma$ vertex.

PACS numbers: 14.80.Er, 12.10.Dm, 12.50.Fk

The study of the characteristics of $Z\gamma$ production in $p\bar{p}$ interactions is an important test of the Standard Model description of gauge boson self-interactions. Since the photon does not couple directly to the Z in the standard electroweak theory, this study is sensitive to anomalous couplings beyond the Standard Model. The most general $ZZ\gamma$ ($Z\gamma\gamma$) vertex function is characterized by a set of four couplings $h_{1-4}^{Z(\gamma)}$ [1], which are dimensionless functions of the four-momenta of the three neutral vector bosons coupled at the $ZV\gamma(V = Z, \gamma)$ vertex. All these couplings vanish at tree level within the framework of the Standard Model. The couplings h_3^V and h_4^V conserve CP, while $h_{1,2}^V$ are CP-violating. Deviations of the h_i^V form factors from zero could be produced by new interactions which become manifest at an energy scale, Λ_Z. A recent study by Baur and Berger [2] discusses the expected experimental sensitivity to non-Standard Model $Z\gamma$ production. For the present analysis, we adopt the assumption of Ref. [2] that the anomalous couplings are regulated by generalized dipole form factors of the form:

$$h_i^V(\hat{s}, M_Z^2, 0) = \frac{h_{i0}^V}{(1+\hat{s}/\Lambda_Z^2)^n},$$

where h_{i0}^V represents the low energy ($\hat{s} = 0$) limit for the couplings, and the values $n = 3$ for $h_{1,3}^V$, and $n = 4$ for $h_{2,4}^V$ have been assumed. Unitarity requires the couplings to asymptotically approach their Standard Model values, and the values chosen for n assure that unitarity is preserved and that all terms in the matrix element proportional to h_{i0}^V have the same high energy behavior.

Moreover, combinations of the h_{i0}^Z are related to the electromagnetic transition moments of the Z boson [3, 4]:

$$\begin{aligned}
d_{Z_T} &= -\frac{1}{\sqrt{2}}\frac{e}{M_Z}\frac{k^2}{M_Z^2}(h_{30}^Z - h_{40}^Z) \equiv -\frac{1}{2}\frac{e}{M_Z}\frac{k^2}{M_Z^2}(\delta^*_{Z_T}) \\
Q_{Z_T}^m &= \frac{e}{M_Z^2}\sqrt{10}(2h_{30}^Z) \equiv \frac{e}{M_Z^2}(q_{Z_T}^m) \\
\mu_{Z_T} &= -\frac{1}{\sqrt{2}}\frac{e}{M_Z}\frac{k^2}{M_Z^2}(h_{10}^Z - h_{20}^Z) \equiv -\frac{1}{2}\frac{e}{M_Z}\frac{k^2}{M_Z^2}(g^*_{Z_T}) \\
Q_{Z_T}^e &= \frac{e}{M_Z^2}\sqrt{10}(2h_{10}^Z) \equiv \frac{e}{M_Z^2}(q_{Z_T}^e)
\end{aligned}$$

Here, $d_{Z_T}(\mu_{Z_T})$ is the transition electric (magnetic) dipole moment, $Q_{Z_T}^e(Q_{Z_T}^m)$ is the transition electric (magnetic) quadrupole moment, and k is the photon energy.

In this paper, we present an analysis of $Z\gamma$ events in which the Z decayed to either e^+e^- or $\mu^+\mu^-$. The best experimental signatures for the presence of anomalous couplings are deviations from the expected Standard Model distributions of the transverse energy of the photon, E_T^γ; the dilepton-photon invariant mass, $M(\ell^+\ell^-\gamma)$; and the lepton-photon opening angles [2]. Limits on pairs of couplings such as (h_{30}^Z , h_{40}^Z) have been previously published based on the number of $Z\gamma$ events observed in the 4.2 pb^{-1} data sample obtained by CDF in 1988/89 [4]. The present analysis, which is based on all data obtained by CDF at the Fermilab Tevatron collider during the 1992/93 run, uses an integrated luminosity of 19.7 ± 0.7 pb^{-1} for the electron decay channel and 18.6 ± 0.7 pb^{-1} for the muon decay channel. This larger data sample has enabled us to place more stringent limits on the existence of $ZZ\gamma$ and $Z\gamma\gamma$ couplings by performing a maximum likelihood fit to the observed E_T^γ distribution, rather than by simply counting events. The number of accepted $Z\gamma$ events is still too few to do a global fit to more than one kinematic distribution and the E_T^γ spectrum was chosen as the most sensitive to non-Standard Model $Z\gamma$ couplings.

The CDF detector has been previously described elsewhere [5] with the specific components of the detector relevant to $(W,Z)\gamma$ observation having been discussed in a companion paper covering $p\bar{p} \rightarrow W\gamma + X$ production [6].

Candidate Z events were selected from samples of inclusive electron and muon data by requiring an isolated charged lepton with $E_T > 20$ GeV in the central region of the detector (pseudorapidity, $|\eta| < 1.0$ for electrons, $|\eta| < 0.6$ for muons). The electron candidate (identified by a central electromagnetic (EM) calorimeter cluster) and the muon candidate (identified by a "stub" track in the central muon drift chambers) were required to have a matching track reconstructed in the central tracking chamber. To gain efficiency, less stringent selections were applied to the second lepton. Specifically, the second electron in Z events was required to have transverse energy, $E_T > 20$ GeV if in the central EM calorimeter, $E_T > 15$ GeV if in the plug region, and $E_T > 10$ GeV if in the forward region. The second muon in $Z \rightarrow \mu^+\mu^-$ candidates was required to have transverse momentum $p_T > 20$ GeV/c, a calorimeter energy deposition consistent with that expected for a minimum ionizing track, and to lie within the $|\eta| < 1.2$ region covered by the central tracking chamber. Additional muon coverage implemented for the 1992/93 run extended the active trigger acceptance for the second muon out to $|\eta| = 1.0$ and also provided additional muon identification and tracking in the central region defined by $|\eta| \leq 0.6$. With the exception of one additional electron trigger [7], these criteria were identical to those used to select Z events for the CDF W/Z cross section ratio analyses [8], and full details of the Z selection are given in those papers. The final Z candidate selection required that the invariant mass of the charged lepton pair was in the range $70 - 110$ GeV/c^2 for e^+e^- and $65 - 115$ GeV/c^2 for $\mu^+\mu^-$. The total number of Z events selected was 1237 in the electron channel and 507 in the muon channel.

The criteria used to select photon candidates in the Z events are identical to those used for the $W\gamma$ analysis of Ref. [6]. These criteria include the requirement that the photon candidate lie within a defined fiducial region of the central EM calorimeter, have transverse energy $E_T > 7$ GeV, have an angular separation (in pseudorapidity, η, and azimuthal angle, ϕ), $\Delta R_{l\gamma} = \sqrt{\Delta\eta^2 + \Delta\phi^2} >$ 0.7, between the photon and the *closest* charged lepton, and be isolated from nearby particles in the event. The E_T^γ requirement is imposed on the photon after the energy has been corrected for calorimeter non-uniformities and the global energy scale. Calorimeter isolation is imposed, within a cone of $\Delta R = 0.4$ centered on the photon direction, by requiring that the additional transverse energy in the cone (E_T^4) be less than 15% of the photon transverse energy. Tracking isolation is imposed by requiring that the sum of the transverse momentum of all tracks within a cone of $\Delta R = 0.4$ centered on the photon cluster be less than 2 GeV/c. Tracks included in this sum must originate from a point that is axially within 10 cm of the interaction vertex. There were 4 events in the electron channel and 4 events in the muon channel that passed all the Z and photon selection criteria.

The main source of background for the $Z\gamma$ process arises from Z + jet events in which the jet fragments to one or more neutral hadrons, e.g. π° or η, that are misidentified as a photon. Additional backgrounds from $Z\gamma$ or Z + jets in which the Z decays to $\tau^{+}\tau^{-}$ were considered and found to be negligible. The fake photon background from QCD jets has been estimated using an independent sample of inclusive jet events recorded by an $E_{\mathrm{T}} > 16$ GeV central photon trigger [9]. To avoid subsequent bias, the photon candidate which triggered each event was removed from the sample. Other jets in the events were counted and those having EM clusters passing our photon cuts were identified. A correction was made to account for the genuine single photon contribution to this background sample. The number of genuine photons was estimated using a χ^2 analysis of the shower shape as measured by the central EM shower maximum detector [9]. The ratio of the number of remaining photon candidates to the number of jets was calculated as a function of E_{T} to estimate the probability of a jet faking a photon. The estimate of the number of fake photon events has been compared to values derived using a Z + jets Monte Carlo calculation [10] plus a parametrized detector simulation, and the agreement is good. The total number of background events estimated from the QCD data sample was $0.4 \pm 0.1 \pm 0.2$ in the electron channel and $0.10 \pm 0.03 \pm 0.04$ in the muon channel. Here, the first uncertainty is statistical and the second systematic. The systematic uncertainty includes contributions from (i) the difference between the experimentally determined QCD background and that determined using the Monte Carlo plus detector simulation, and (ii) the method used to estimate the number of real photons in the QCD background sample. In deriving a combined $Z\gamma$ cross section, we use an overall estimated background of 0.5 ± 0.2 events.

Our Z candidates were selected from the same sample as that used for the W/Z cross section ratio analysis [8] and used the same selection criteria. Furthermore, the lepton identification efficiencies are very weakly dependent on the presence of the photon in the event. Therefore, we have used the efficiencies for the charged leptons from that analysis directly in the present measurement. The additional hardware electron trigger used for our Z sample increased the overall electron trigger efficiency from 0.892 ± 0.003 for the cross section ratio analysis to 0.952 ± 0.003. The combined E_{T} -independent efficiency for central photons was $(81.2 \pm 2.3)\%$. The calorimeter isolation requirement gave an E_{T} -dependent photon acceptance that was $(90 \pm 1)\%$ at $E_{\mathrm{T}} = 7$ GeV and became constant at $(99 \pm 1)\%$ for $E_{\mathrm{T}} > 25$ GeV. The efficiencies thus determined were used in a Monte Carlo simulation of the CDF detector to determine the overall acceptance of $Z\gamma$ events with a central photon of $E_{\mathrm{T}} > 7$ GeV. The details of the determination of the photon acceptance and detection efficiency are given in Ref. [4]

The photon E_{T} distribution for the combined electron and muon data is shown in Fig. 1a while Fig. 1b shows the $M(\ell^{+}\ell^{-}\gamma)$ distribution. The calculation of Baur and Berger [2], available as a Monte Carlo program, has been combined with the simulation of the CDF detector to determine the expected numbers of $Z\gamma$ events and their characteristics as a function of the assumed values of h_{i0}^{V}. The event generation used the MRSD$'_{-}$ structure functions [11]. One of the most striking signatures for anomalous couplings in $Z\gamma$ production would be an increase in the number of photons with $E_{\mathrm{T}}{}^{\gamma} \gtrsim 40$ GeV. The histograms indicate the sum of the expected signal for the Standard Model as determined by the Monte Carlo simulation plus the estimated background. Although there is no significant deviation from Standard Model expectations seen in any of the distributions, we note the presence in our muon sample of an event with $E_{\mathrm{T}}^{\gamma} \sim 64$ GeV and $M(\mu^{+}\mu^{-}\gamma) \sim 188$ GeV/c^2.

The combined electron and muon channel cross section times branching ratio for central photons with $\Delta R_{\ell\gamma} > 0.7$ and $E_{\mathrm{T}}^{\gamma} \geq 7$ GeV is $[\sigma \cdot B(Z+\gamma)]_{\mathrm{exp}} = 5.1 \pm 1.9(\mathrm{stat}) \pm 0.3(\mathrm{syst})$ pb.

The Standard Model expectation is $[\sigma \cdot B(Z+\gamma)]_{\rm SM} = 5.2 \pm 0.6(\text{stat} \oplus \text{syst})$ pb. The electron and muon channel results have been individually corrected for acceptances and efficiencies. The systematic uncertainty in the experimental cross section arises mainly from the photon background determination but also includes a $\pm 3.6\%$ uncertainty from the integrated luminosity. The systematic uncertainty in the expected Standard Model cross section is almost entirely due to variations from structure function choice, but includes small contributions from the assumed Q^2 scale and transverse momentum distribution of the $Z\gamma$ system.

Limits on anomalous $Z\gamma$ couplings are quite sensitive to the form factor scale, Λ_Z, through the inverse dependence of the unitarity limit on this scale [2]. We find the experimental limits on the couplings reach the limit set by unitarity for $\Lambda_Z \simeq 500$ GeV, and we have, therefore, fixed the scale parameter at this value. We obtain limits in a pairwise fashion, setting all other couplings to zero. A log-likelihood fit was performed to the photon $E_{\rm T}$ spectrum parametrized by the couplings. For fitting purposes, the likelihood function was calculated for a range of h_{i0}^V values as the product of the probabilities that, for the expected number of events in each $E_{\rm T}$ bin smeared by our systematic uncertainties, the number of observed events would have been produced. Figure 2 shows the contours for the 68% and 95% confidence levels for $ZZ\gamma$ and $Z\gamma\gamma$ couplings along with the unitarity constraint. The 95% confidence level limits for the individual parameters using the combined $e+\mu$ data and assuming all other anomalous couplings are zero are as follows:

$$\begin{array}{lcc} ZZ\gamma: & -3.0(-2.9) < h_{30}^Z \ (h_{10}^Z\ ) < 2.9 & -0.7 < h_{40}^Z \ (h_{20}^Z\ ) < 0.7 \\ Z\gamma\gamma: & -3.1 < h_{30}^\gamma \ (h_{10}^\gamma\ ) < 3.1 & -0.8 < h_{40}^\gamma \ (h_{20}^\gamma\ ) < 0.8 \end{array}$$

From the preceding $ZZ\gamma$ coupling limits we extract bounds on the electromagnetic transition moments of the Z. Assuming the other moments to be equal to their Standard Model value of zero, the 95% confidence level interval for $\delta_{Z_{\rm T}}^*$, which is related to the electric dipole transition moment is $-1.1 < \delta_{Z_{\rm T}}^* < 1.1$. The quantity, $q_{Z_T}^m$, related to the magnetic quadrupole transition moment, has a 95% confidence interval of $-6.0 < q_{Z_T}^m < 6.0$. Allowing simultaneous variations of both moments results in the bounds shown by the contours in Fig. 3. The transition magnetic dipole and electric quadrupole moment related quantities, $g_{Z_{\rm T}}^*$ and $q_{Z_T}^e$, lie within identical contours to those shown for $\delta_{Z_T}^*$ and $q_{Z_T}^m$.

In conclusion, we have observed $Z\gamma$ production in $p\overline{p}$ collisions. The rate and the kinematic distributions agree well with Standard Model expectations. Fitting the photon $E_{\rm T}$ distribution to extract limits on anomalous couplings has significantly improved the bounds from those previously obtained by CDF via counting the number of produced $Z\gamma$ events.

We thank the Fermilab Accelerator Division for exceptional performance of the Tevatron during the 1992/93 Collider run and the support staff of our collaborating institutions for their contributions to the success of the CDF detector. This work was supported by the Department of Energy; the National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science, and Culture of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Alexander von Humboldt-Stiftung and the A.P. Sloan Foundation. We thank U. Baur, F. Boudjema, R. Cousins, and D. Drijard for helpful discussions.

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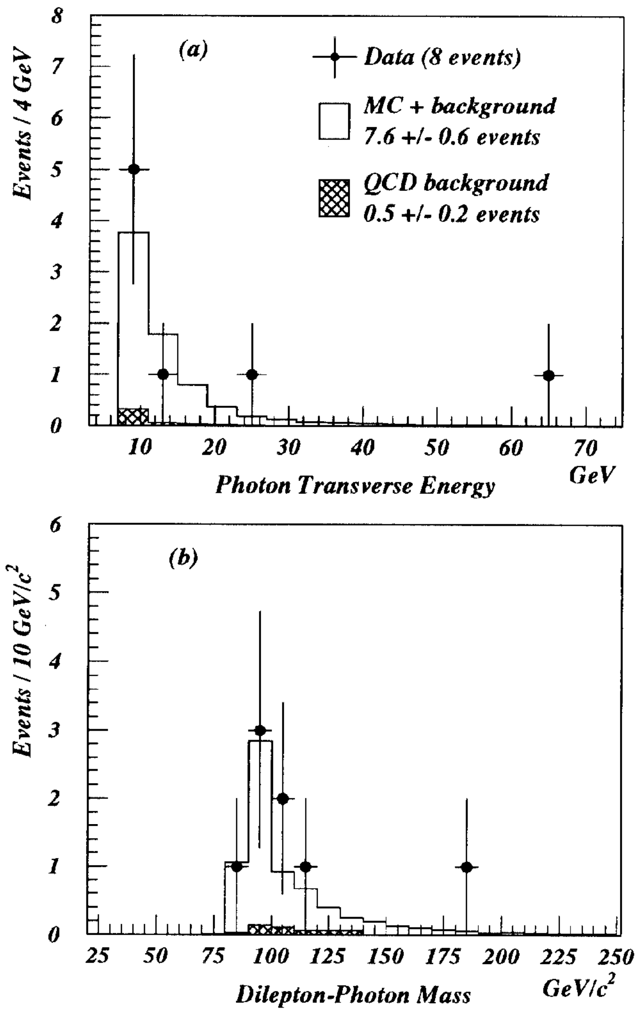

Figure 1: (a) The distribution of photon transverse energy, E_T^γ, for electron and muon channels combined (points). The Standard Model plus background expectation is shown as the open histogram. The cross-hatched histogram for QCD background is derived from the E_T dependent probability for a jet to pass our photon selection criteria (see text). (b) The $\ell^+\ell^-\gamma$ invariant mass distribution for electron and muon channels combined. The Standard Model Monte Carlo signal plus background and background only contributions are again shown for comparison.

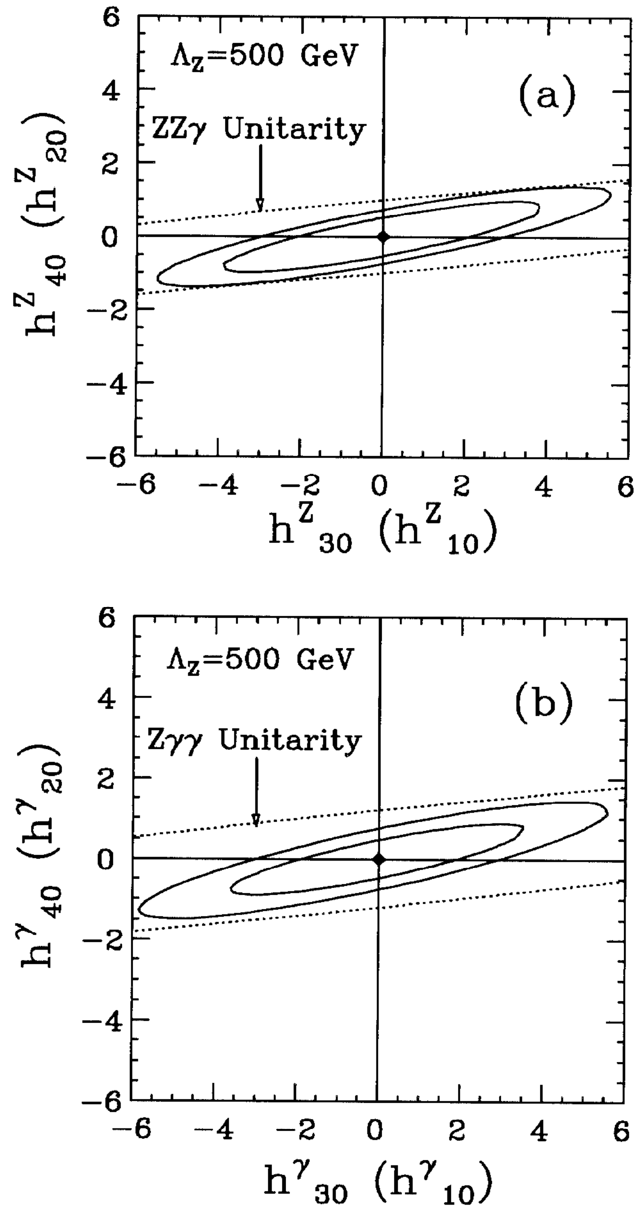

Figure 2: Contour plots of the 68% and 95% confidence limits on the (a) $ZZ\gamma$ and (b) $Z\gamma\gamma$ anomalous couplings. The parentheses indicate that the limit contours for the $h_{10}^{Z,\gamma}$, $h_{20}^{Z,\gamma}$ pair are the same as those for the $h_{30}^{Z,\gamma}$, $h_{40}^{Z,\gamma}$ pair.

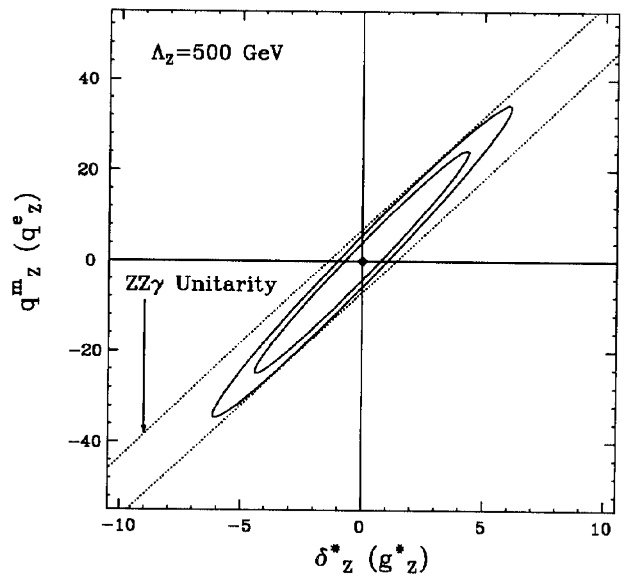

Figure 3: Contour plots of the 68% and 95% confidence limits on the $ZZ\gamma$ transition moments. The symbols are defined in the text.